Artificial Intelligence in Integrated Diagnostics of the Rotating System with an Active Magnetic Bearing

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Abstract. An implemented and experimentally verified diagnostic system for the rotating mechatronic system of machines with an active magnetic bearing is presented. An additional module that controls the correctness of its operation, employing artificial intelligence methods, is proposed. The results of preliminary investigations which will allow for an expansion of the diagnostic pattern base necessary to develop of an expert advisory system are given.

Keywords: AI, fuzzy logic, neutral networks, magnetic bearing, diagnostics.

1 Introduction

A key issue in operation of modern machines is their reliability. Critical machines are equipped with diagnostic systems that process numerous measurement data registered during their work.

The most important problem is an analysis and then a right interpretation of these data and determination of mutual correlations between process parameters and the machine dynamics. As a result, optimization of motion parameters and, particularly, an increase in reliability of the machine are possible. Advanced computational methods let us derive models of the theoretical data obtained experimentally and conduct a wide range of analyses and optimization of geometrical, flow and dynamic parameters of machines.

In the operating diagnostics of machinery, special attention should be paid to non-invasive methods for detecting defects that can be performed directly on the object, without interrupting the machine operation. These methods mainly rely on registration of selected measurement signals of the working machine, and then they are subject to a detailed analysis in terms of appearance of characteristic symptoms of damage.

The paper presents a diagnostic system, which was implemented and experimentally verified on the real test stand of the rotating mechatronic system with an active magnetic bearing. An additional module that controls the correctness of the system operation, using artificial intelligence methods, is proposed. This module is intended to aid the operation of the existing diagnostic system. The results of preliminary investigations which will allow for an expansion of the diagnostic pattern base necessary to develop of an expert advisory system are presented.

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2 Test Stand

In many areas of technology, also in mechanical engineering, there are more and more devices whose design is only possible through an integration of mechanical, electrical, electronic and information equipment. These devices are called mechatronic systems.

An example of an unconventional solution to a bearing node is a mechatronic system of an active magnetic bearing. The system of active, digitally controlled magnetic bearings provides an interesting alternative in the design of modern machines, whose task is to implement the technological processes involved in meeting specific operational requirements (operation in a range of very low or high temperatures, in chemically aggressive environments, or in the vacuum) [7, 8].

The magnetic rotor suspension technology in machines is qualitatively different if compared with conventional bearing solutions. Its characteristic feature is non-contact levitation of the machine rotor in the magnetic field generated by an automatic control system, which allows for controlling dynamics of the rotor during its motion.

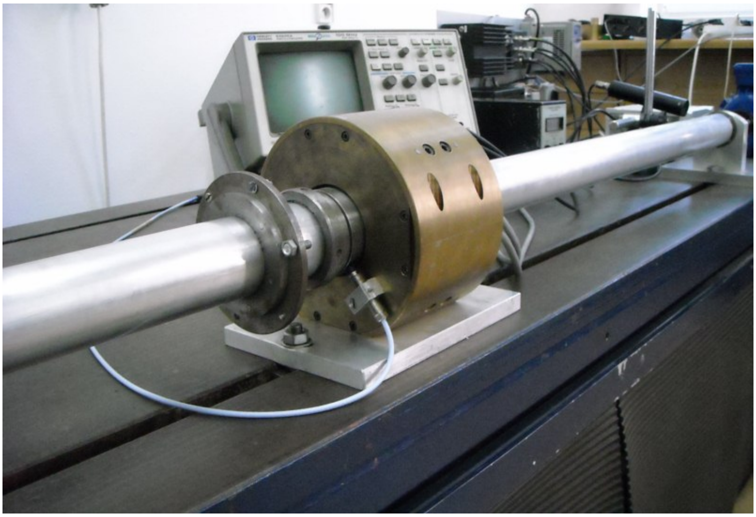

Fig. 1. Test stand of the rotating system with a magnetic bearing

The experiment was carried out on the test stand (Fig. 1), whose rotating shaft is a thin-walled tube made of duralumin of the external diameter equal to 54 mm and the 2 mm wall thickness, supported with two roller bearings mounted on both ends. Between these bearings, there is a system of active magnetic auxiliary support. It is driven by an electric motor, controlled by an inverter and connected to the shaft by a flexible coupling membrane. The mass of the rotating system is 4.85 kg and the length of the shaft – 1923 mm.

3 Magnetic Reaction Forces of the Bearing

A unique feature of magnetic bearings is a possibility to determine, with an indirect method, magnetic reaction forces generated in the axes of control, on the basis of measurements of currents and movements for given values of the electromagnet constants. The knowledge of forces acting in a rotating system of the machine has an important diagnostic value, because the cause of vibration, which occurs earlier than the effect, i.e., a response of the vibrating structure [5, 8], can be observed.

A reaction vector of the magnetic bearing is a sum of the forces generated by bearing electromagnets and changes in each control cycle. The component of the magnetic reaction F_{xmag} for the axis x is determined with the relationship:

$$F_{x\,mag} = K_{XT}\frac{I_{XT}^{\;2}}{s_{XT}^{\;2}} - K_{XB}\frac{I_{XB}^{\;2}}{s_{XB}^{\;2}} \tag{1}$$

The component value of the magnetic reaction F_{xmag} (Fig. 2) for a single control axis is related to the measured average values of the control current of the electromagnets I_{XT}, I_{XB} in a given period of control and the values of the magnetic slot s_{XT}, s_{XB} (*T – top*, *B – bottom*).

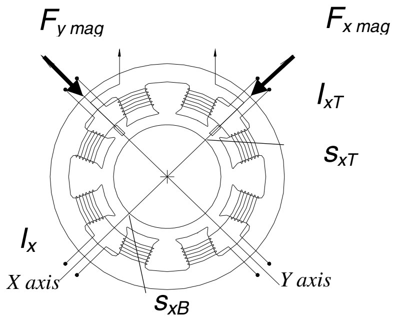

Fig. 2. Components of the magnetic reaction

The values of slots are found by measurements of instantaneous values of the journal position with respect to the bush center of the known clearance. The instantaneous values of the journal position are measured with a measuring system, specially designed for this purpose, being an integral part of the diagnostic system for control of the bearing operation. A value of the electromagnet constant K depends on its design parameters and can be calculated from the theoretical dependence or determined experimentally [8].

4 Characteristics of the Diagnostic System and Its Software

The specificity of the real object imposes special demands associated with a necessity of construction of the diagnostic system, which controls simultaneously the functioning correctness of the rotating system and the control effectiveness of its lateral vibrations. An analysis and interpretation of the measurement data collected during the operation of the machine rotating system with a magnetic bearing are performed with the developed diagnostic software.

The signals for a database of the diagnostic system come from sensors installed in the magnetic bearing. They measure the journal position in two axes of control and the current in the windings of electromagnets. These sensors are an integral part of modules for control of the bearing operation. Additional measuring systems measure the frequency of the shaft rotation and the temperature of electromagnets windings. For collecting and recording the data necessary in the diagnostics of the mechatronic rotating system, a USB-4716 Advantech module equipped with a USB interface that provides the appropriate speed and accuracy of data transmission in measurement applications is used. The USB module does not require any additional power source. Clips for connecting all input/output signals are placed on the device casing (Fig. 3).

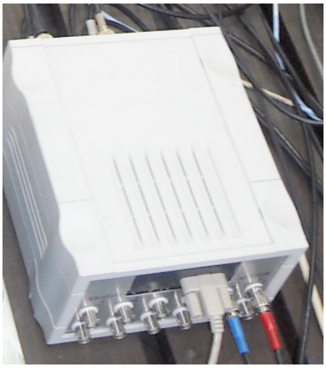

Fig. 3. Acquisition module of diagnostic data

The existing diagnostic software of the rotating system with an active magnetic bearing covers two stages of operation:

Stage I – ”on-line” mode:

- performance of test functions of the system along with control of the magnetic bearing at the starting moment, which allows one to diagnose the system dynamics for the fixed shaft in the phase of its suspension in the magnetic bearing (rotational frequency is equal 0). On their basis, computational procedures allow one to evaluate the bearing operation correctness and the integrality of the power transmission shaft. After the end of the tests, a signal of readiness to initiate the drive is generated;
- data collection and recording in real-time after the drive starts its operation (with the rotating shaft), comprising: the start-up, the shut-down, operation at the nominal rotational frequency and operation in the emergency mode (autorotation mode);
- “*on-line*” recording and control of parameters of the system operation during each phase and selection and reduction of the saved data files in the non-volatile memory that concerns mainly untypical behaviors of the system; signaling and generating

different level alarms in cases of exceeding critical values for the operation of the power transmission system or the bearing system.

Stage II – ”off-line” mode:

- data decoding recorded during the first stage of diagnostic software operation, collected in the memory of the diagnostic system by means of the external computer and some special software for this task;
- analysis of the collected data concerning temporary states of the system operation (the start-up, the shut-down) and untypical behaviors, and a graphic presentation of evolution of the shaft trajectory versus time, Bode plots, characteristics of changes in values of magnetic forces, temperature fluctuations of electromagnets windings, etc.

5 Concept of the System Development with Artificial Intelligence Methods

In the next stages of the work on the diagnostic system, further development of its software which will include a generation module of diagnostic hypotheses based on modern methods such as neural networks, Bayesian belief networks and fuzzy logic elements, is planned.

The proposed concept of the diagnostic system for the machine rotating system with an active magnetic bearing will perform the following tasks:

- diagnosis – determine the current state of the machine on the basis of the analysis carried out by the existing diagnostic system,
- genesis – identify the causes of the current state of the machine,
- forecast – predict further possible changes in the machine state.

The implementation of these tasks will minimize the probability of unforeseen problems in the machine operation and proper planning of operational and repair activities.

A proper identification of the current state of the machine must have a reference to the information about the history of the object and progressive changes occurring in the machine during its operating time. The information about the history of state changes during operation, and the correctly described current state of the machine allow one to predict the future behavior of the machine.

On one hand, a concept of the diagnostic system includes a database of diagnostic patterns, and, on the other hand, an archival database of measurements made during the period of the machine operation. The reliable data from the database of diagnostic patterns are designed to deliver an accurate diagnosis, and, thus, to make right decisions. An accurate diagnosis on the state of an object can be achieved with different methods of assessment. The underlying idea of these methods is common. It involves finding patterns in a database of diagnostic patterns which are most similar to the currently presented ones for the measurement. For the pattern chosen with this method, there are given factors whose coefficients determine the qualitative and quantitative information on possible irregularities occurring in the machine state.

The Main Elements of the Proposed Module to Generate Hypotheses for the Diagnostic System Are as Follows:

- a database of diagnostic patterns – including the results of calculations of specialized mathematical models, taking into account an impact of the machine state on features of the proposed diagnostic signals,
- a database of measurements – including the results of measurements made on the diagnosed object,
- an acquisition block of diagnostic signals – a part of the system responsible for the collection of measurement data from the test object,
- a diagnostic inference block – a part of the system in which methods and rules of inference to assess the state are implemented,
- a diagnostic results block – which stores the results of the object state diagnoses,
- a operational decisions block – whose task is to determine the operating instructions,
- processing procedures – a set of procedures for processing both the measured data and the data from the database of diagnostic patterns.

Procedure Algorithm:

- the database of diagnostic patterns stores diagnostic patterns for various stages of magnetic bearings operations,
- the diagnostic signals are taken from the test object by the block of data acquisition,
- the collected data in the block of data acquisition are written to the measurement database,
- in the diagnostic inference block, there is a choice of data processing procedures for a particular measurement and processing data stored in the pattern database for a given operation stage of the bearing,
- the processed data from both databases are evaluated by the chosen diagnostic method. As a result of the diagnostic evaluation, indicators characterizing the state of the machine are given. They are saved in a block of diagnostic results,
- on the basis of the results of the diagnosis in a block of operational decisions, exploitation instructions and dates of the next technical machine examinations are determined.

The main elements of the proposed diagnostic system, from the standpoint of accuracy and reliability of the diagnosis, are as follows: a database of diagnostic patterns, a diagnostic inference block and a data acquisition system. The data acquisition system is directly responsible for providing actual measurement results for the diagnostic assessment phase and is one of the main elements of the diagnostic system.

In the diagnostic inference block of the designed system, data processing with artificial intelligence methods, which use their knowledge of the possible states of the machine, takes place. The data needed by neural networks to learn and to determine membership functions are derived from the database of diagnostic patterns obtained from the solution to the mathematical model and processing them in an appropriate way, depending on the applied method of inference.

6 Verification of Proper Operation of the Designed Module

According to the implementation concept of an expert diagnostic system that controls the proper operation of the active magnetic bearing, a neural network which reacts to changing signals on its input was developed. To provide the current state of the tested system, the neural network learning process must be conducted. It is necessary to construct a diagnostic patterns database.

Figure 4 illustrates preliminary trials of the conducted analysis. The designed neural network was to determine the parity of ones occurring in the input values string. For this purpose, a database consisting of a sequences of 6 digits 0 or 1, and the seventh value determining the ones parity in the given string using the digit 1 or their odd parity with the digit 0 was created. The neural network was trained on the basis of an incomplete database (52 input data sequences out of 64 possible). To verify the correctness of the proposed method, the data that were not included in the input learning base were used. The developed neural network interpreted the task correctly (Fig. 4).

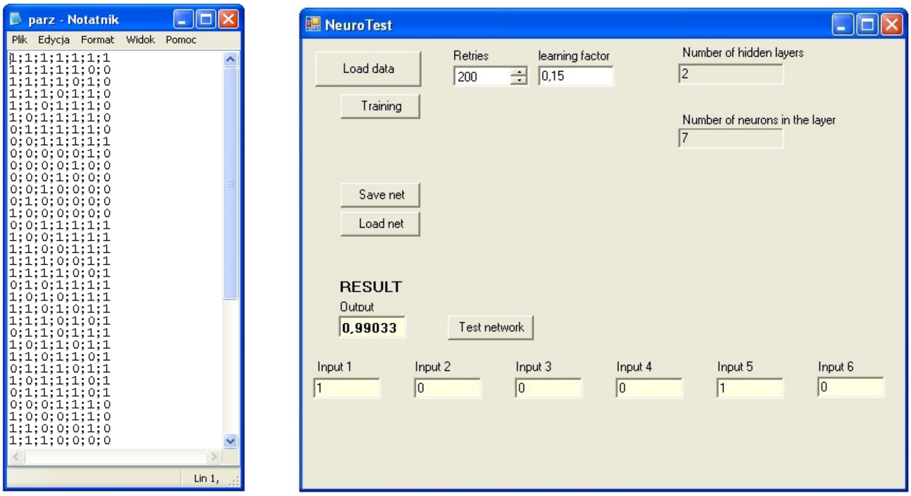

Fig. 4. Verification of the proper operation of the neural network

The verified neural network can be used in a real system to control the proper operation of the tested magnetic bearing.

The designed system for recording measurement data during the operation of magnetic bearings and the possessed knowledge of the object enabled generation of the diagnostic pattern database which maps the operation of the tested rotating system. The diagnostic pattern database consists of records containing 6 fields for variables from the simultaneous measurement of shaft displacements in the magnetic bearing in two control axes and four current values generated by the electromagnets. The last, seventh value of the knowledge base is created to determine the proper operation of the rotating system in the form of 0 or 1 (Fig. 5a).

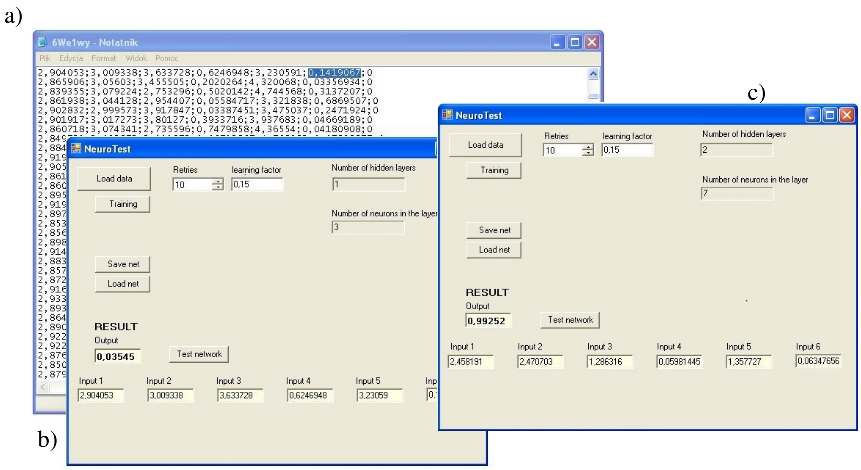

Fig. 5. Analysis of proper operation of magnetic bearings using a neural network: 5a) database of diagnostic patterns; 5b) magnetic bearing malfunction; 5c) correct operation of the magnetic bearing

The neural network learning process was conducted using the available knowledge base. After entering 6 values related to the analyzed operating phase of the tested system to the input of the trained network, the designed module properly evaluated the state of the object giving the value close to zero, corresponding to the incorrect action of the bearing in the output (Fig. 5b). Figure 5c shows correct functioning of the bearing, which was interpreted by the system by attaining a value close to 1 in the output.

After the learning process based on the incomplete knowledge base, this system will provide a current state of the magnetic bearing under test.

7 Summary

To construct an expert advisory system, there is a need to collect an extensive knowledge base, covering completely the problem under analysis. The experience gained in verification of the correctness of the existing diagnostic system based on traditional methods of analysis will serve as the basis for development and correctness verification of the module using artificial intelligence methods to control the proper operation of the mechatronic rotating system. The preliminary results encourage further analysis of the problem using a neural network.

The next stage for development of the diagnostic module will consist in choosing appropriate sequences of input data and learning parameters of the neural network (a number of hidden layers, a number of neurons in the layer, learning rate and a number of repetitions) in order to interpret correctly the current state of the object by the program.

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